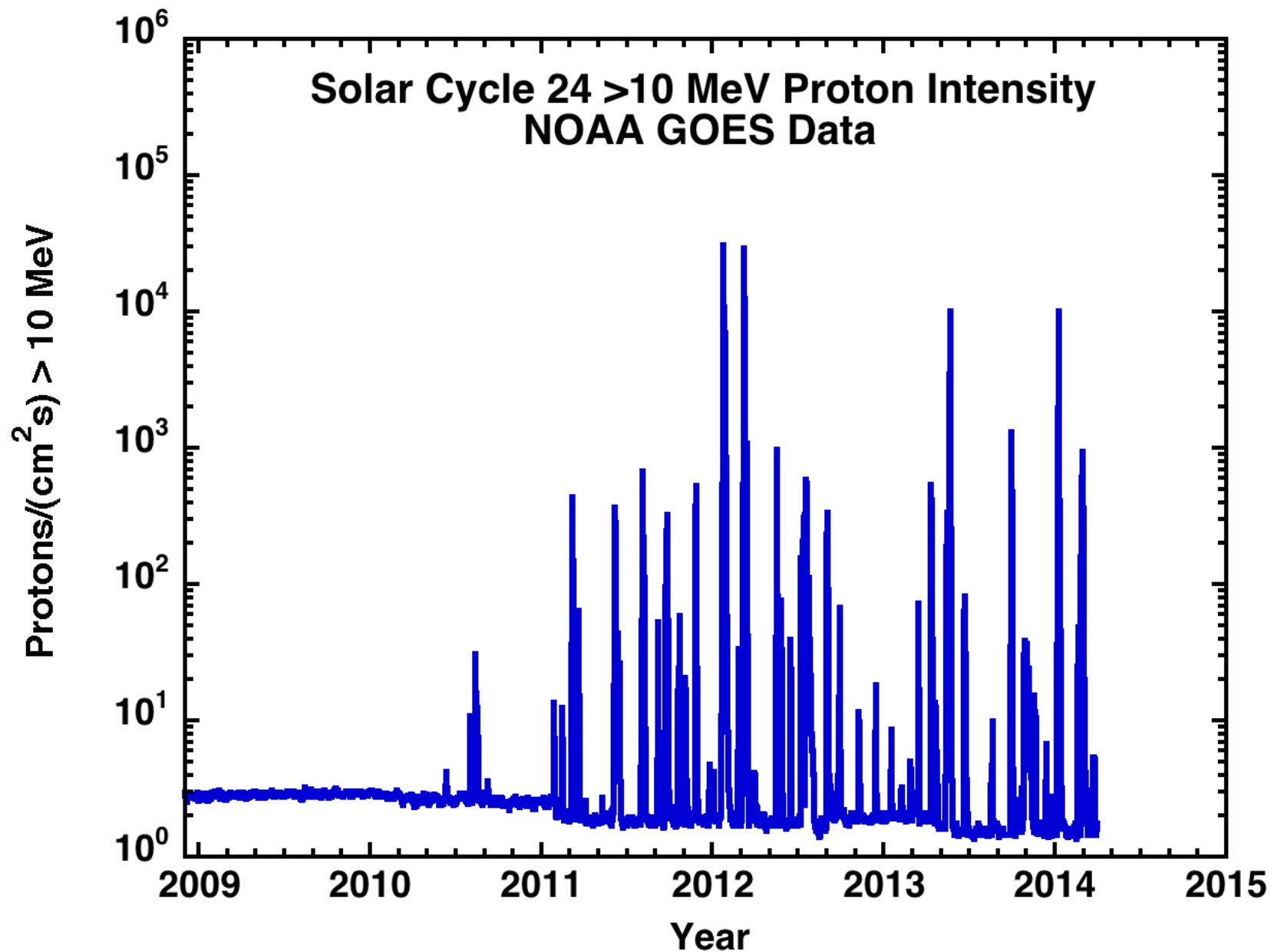


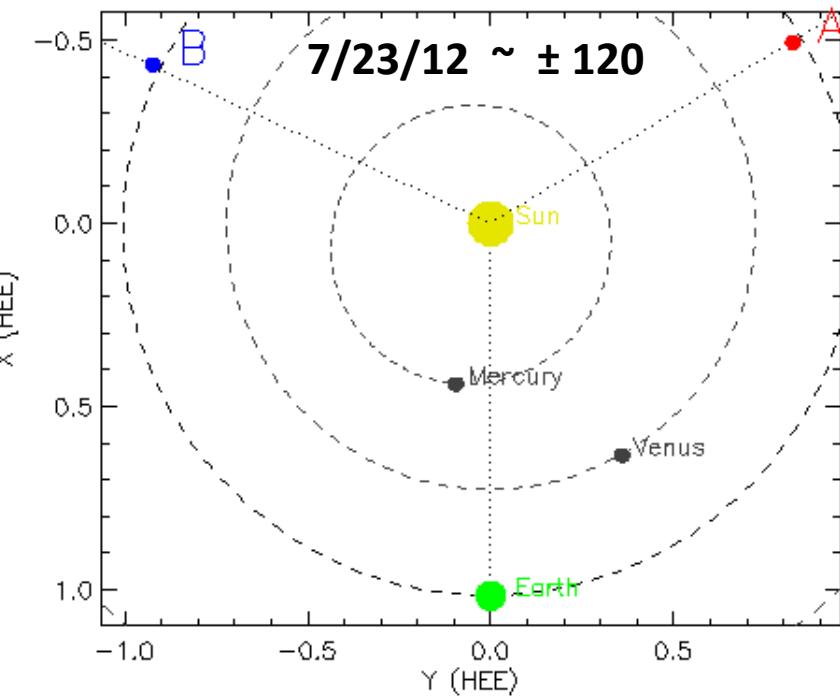
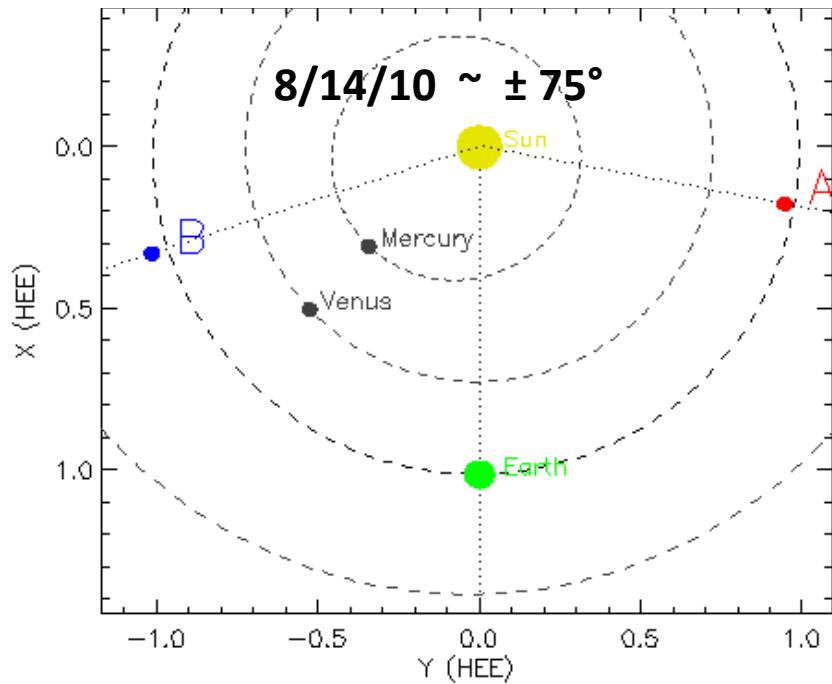
Solar Proton Events of Solar Cycle 24

**Richard Mewaldt
Caltech**

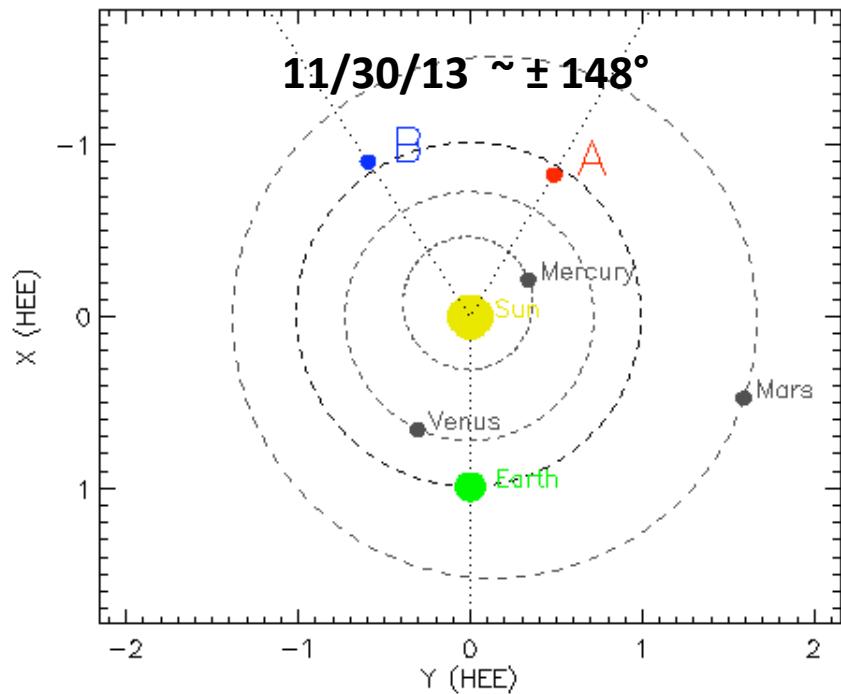
**With Thanks to
C. M. S. Cohen, I. G. Richardson
and T. T. von Rosenvinge**

**Space Weather Workshop
Boulder, Colorado
4/11/14**

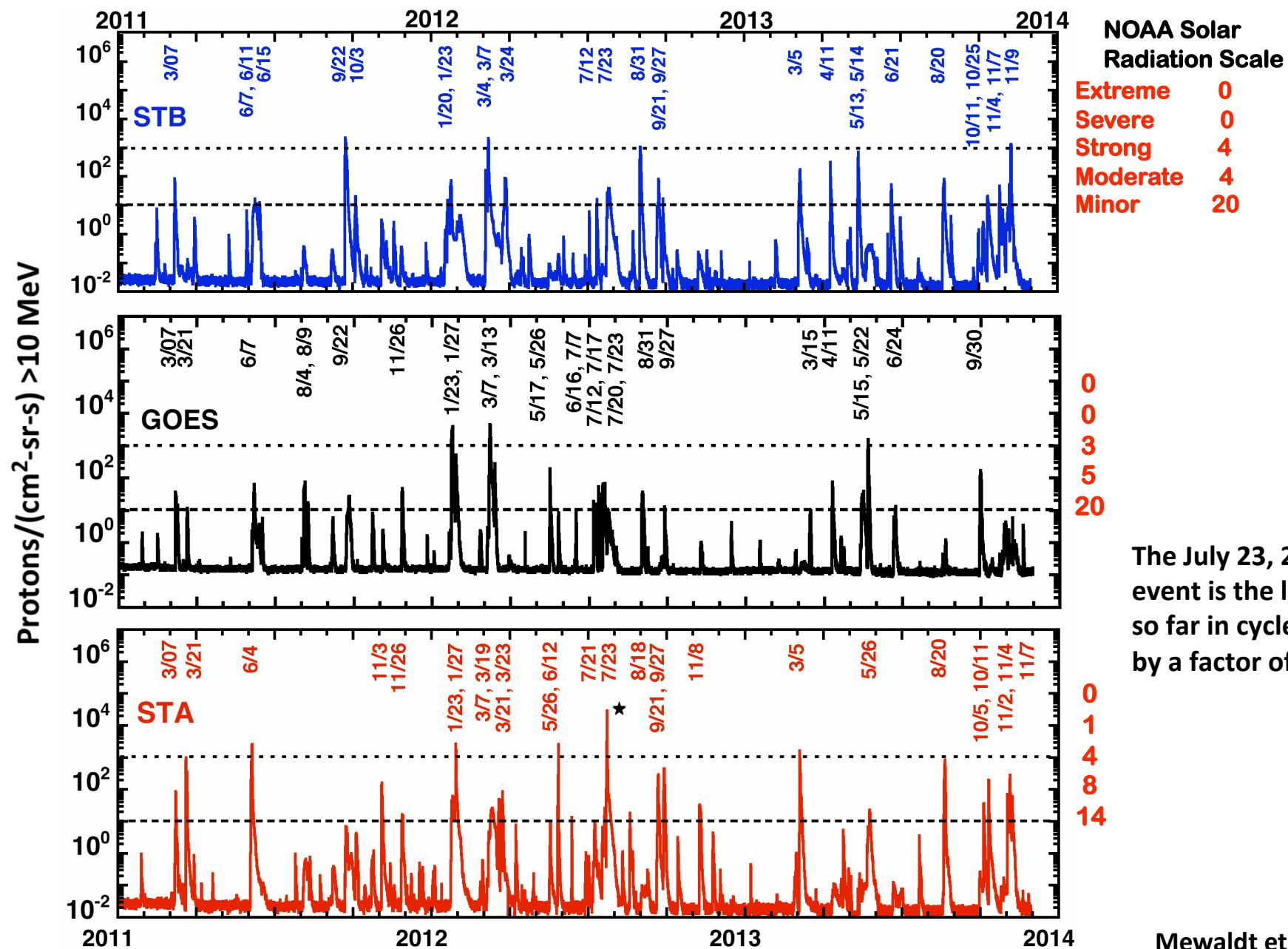




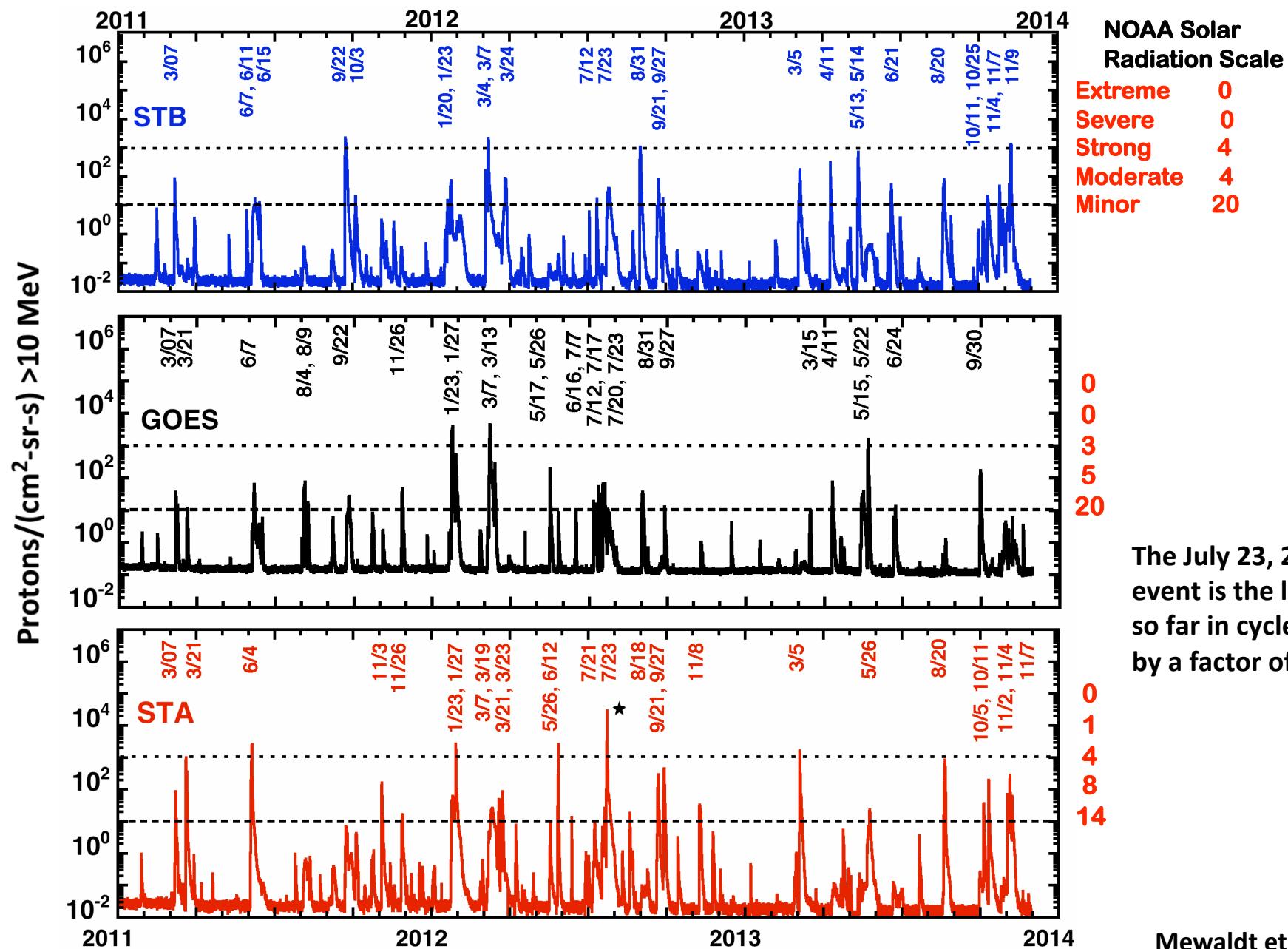
Where was STEREO??



>10 MeV Proton Intensity at STEREO-B, Earth, and STEREO-A



>10 MeV Proton Intensity at STEREO-B, Earth, and STEREO-A



Solar Cycle 24

Number of Single and Multiple “GOES Events”

Through November, 2013 there were a total of 55 separate solar eruptions that met the NOAA criterion at one or more spacecraft

| A | Earth | B | A+E | E+B | B+A | A+B+E |
|----|-------|----|-----|-----|-----|-------|
| 28 | 28 | 27 | 4 | 5 | 7 | 6 |

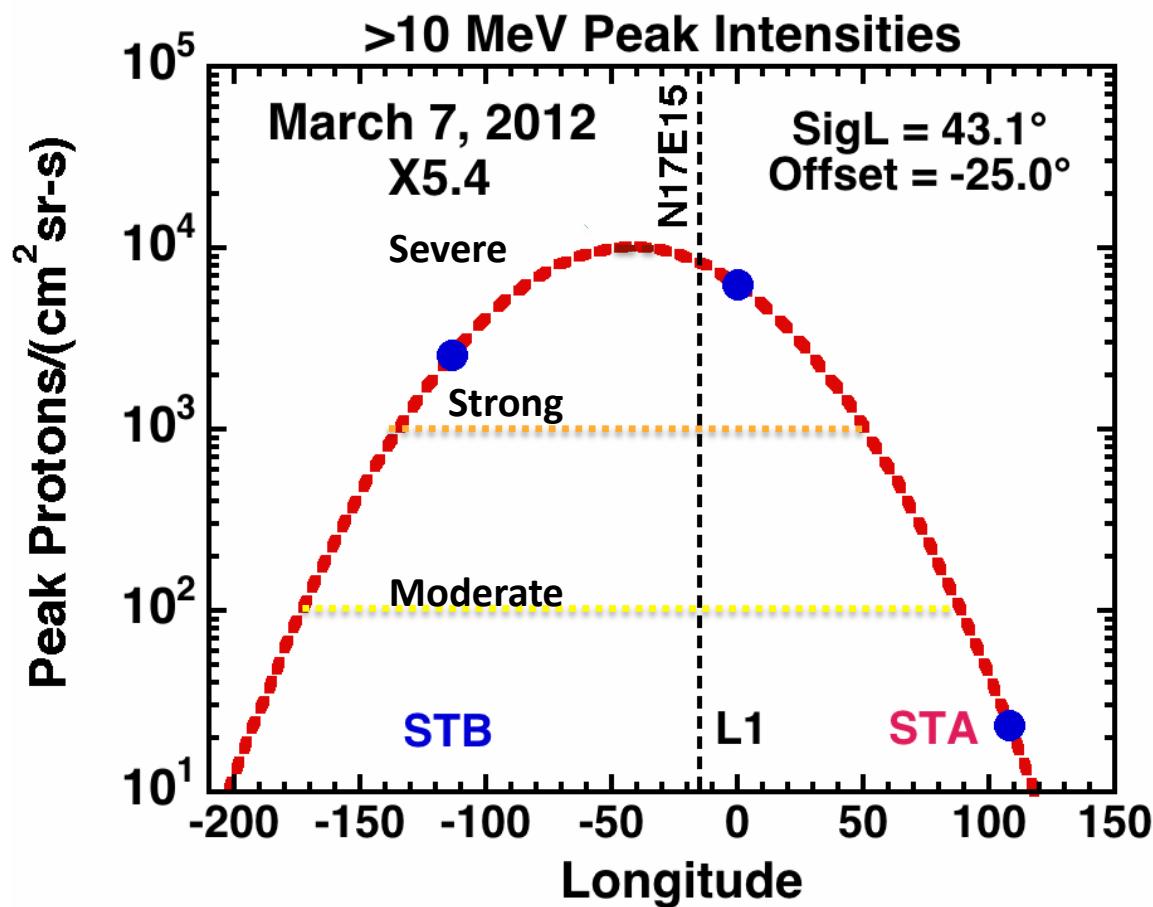
- About 40% of the time two or more spacecraft saw a “GOES” event.
- For the following events all 3 locations had proton intensities ≥ 10 protons/(cm²sr-s)

3/7/11, 6/6/11, 1/23/12, 3/7/12 7/23/12, 9/27/12

If we require only “an increase in >10 MeV protons at each spacecraft, there were >50 events observed at all 3 spacecraft.

See also Mewaldt et al. 2013

Example of a Gaussian fit to a Typical SEP Longitude Distribution (see also Lario et al. 2013)

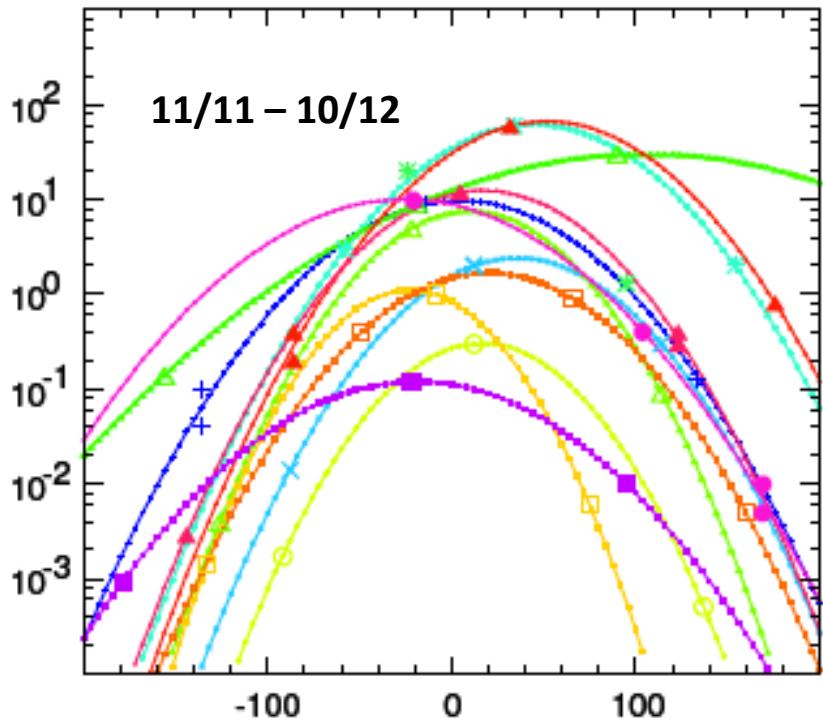
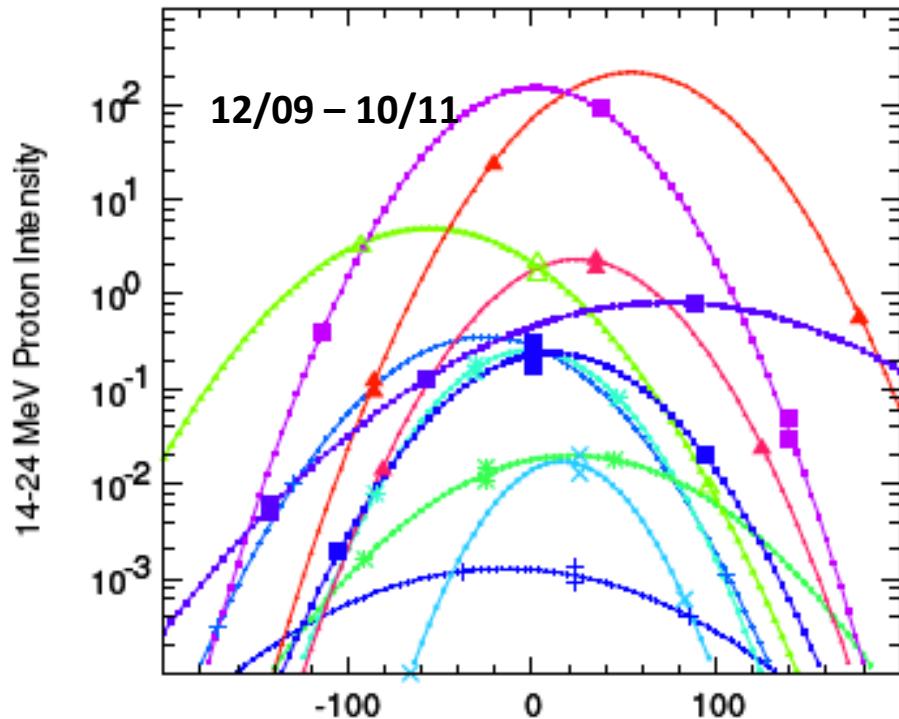


On the NOAA Scale of SEP Events

- The “Severe” event covers ~15°
- The “Strong” event covers ~185°
- The “Moderate” event covers ~260°
- The “Minor” GOES event covers ~320°

Implication: Many space weather events at Earth originate on the far-side of the Sun

**Gaussian Fits to the Longitude Distributions of 14-24 MeV Protons
S/C separated by $>58^\circ$ (Richardson et al., Solar Physics, in press, 2014)**

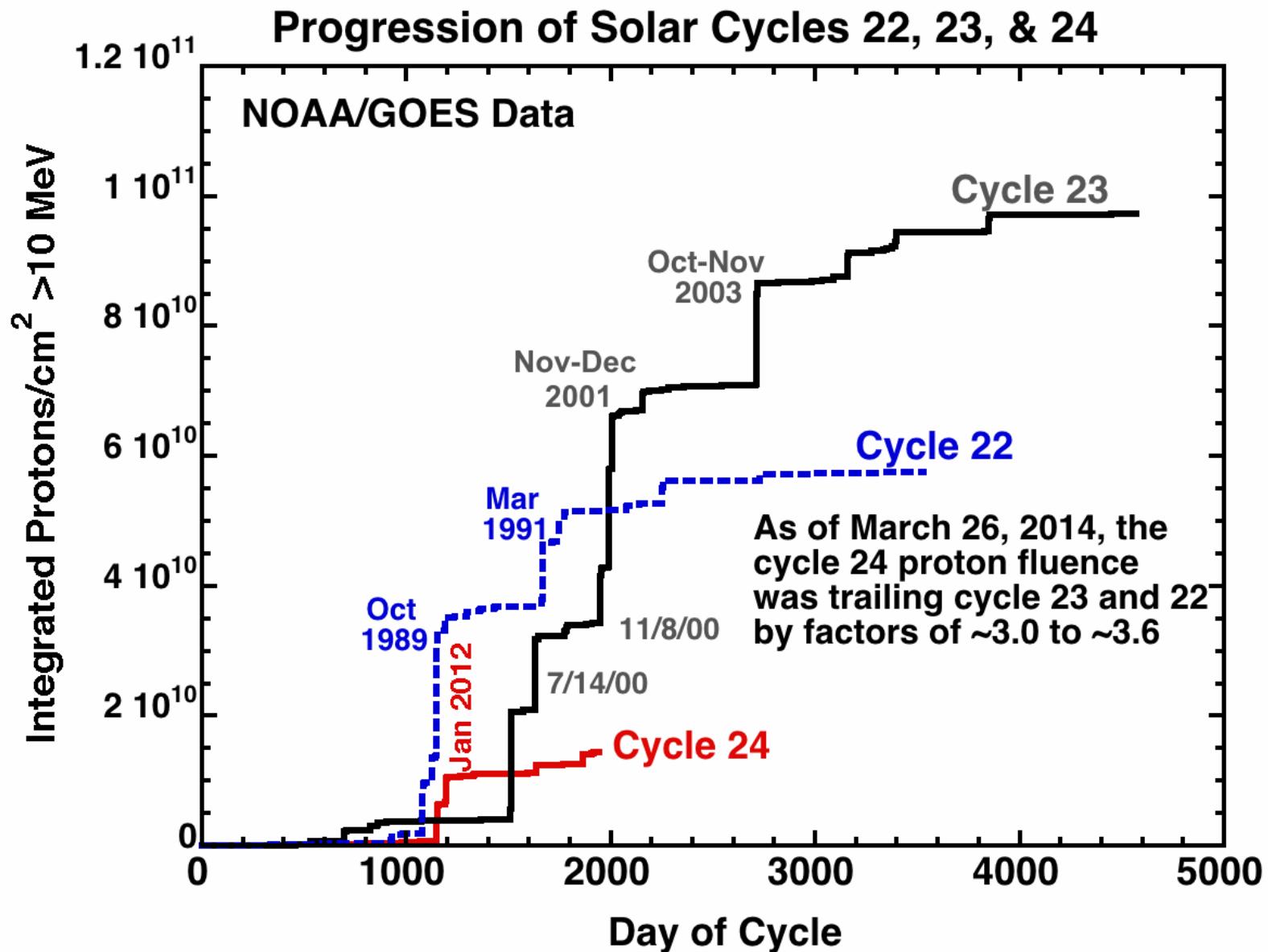


Data from STEREO-A&B/HET and from SOHO/ERNE & EPHIN
Note: 0° longitude is the best solar wind connection point

Mean Fit Parameters: Gaussian sigma = 43°

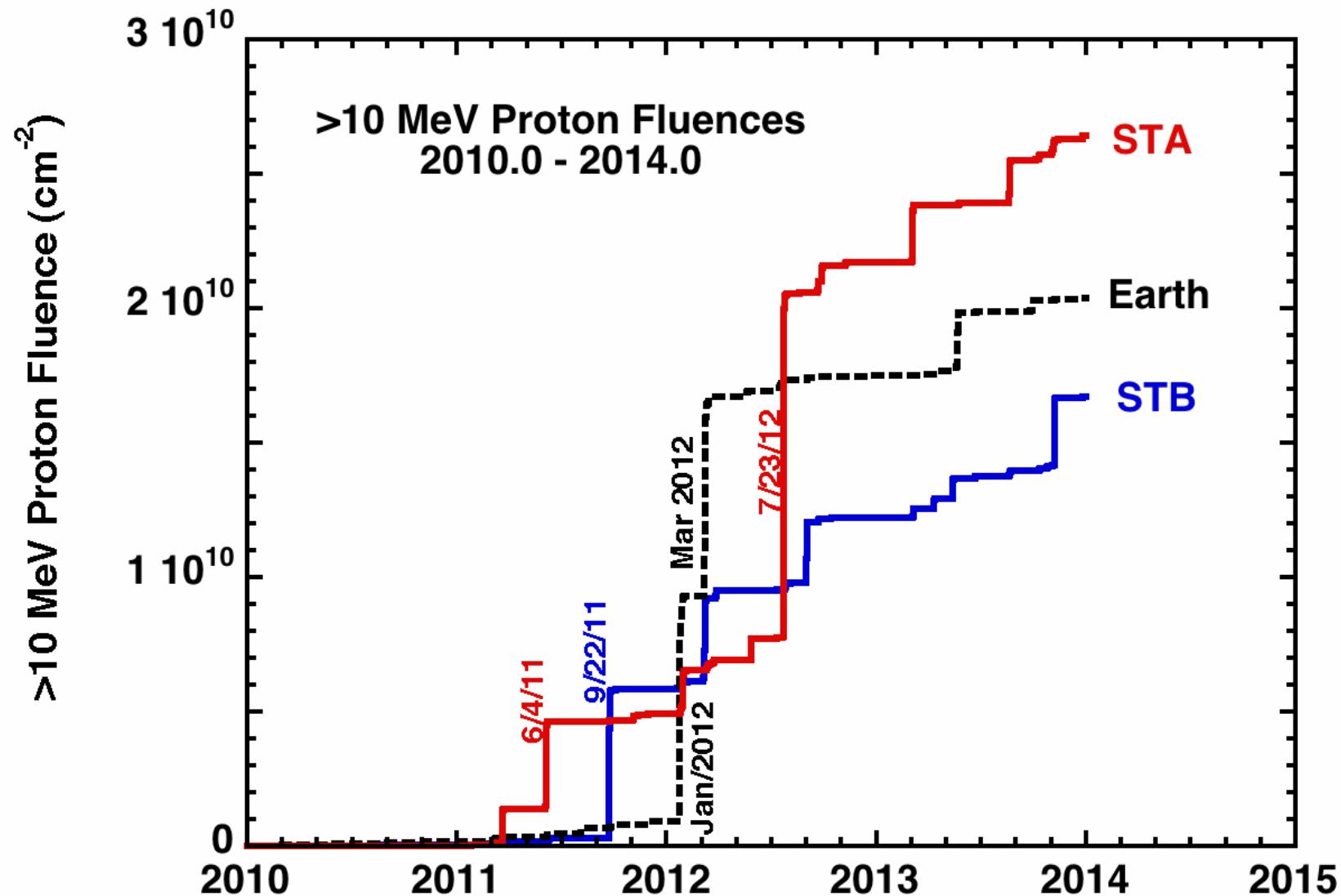
**Peak 15° west of best magnetic connection
point (see also Lario et al. 2013)**

Richardson et al. 2014

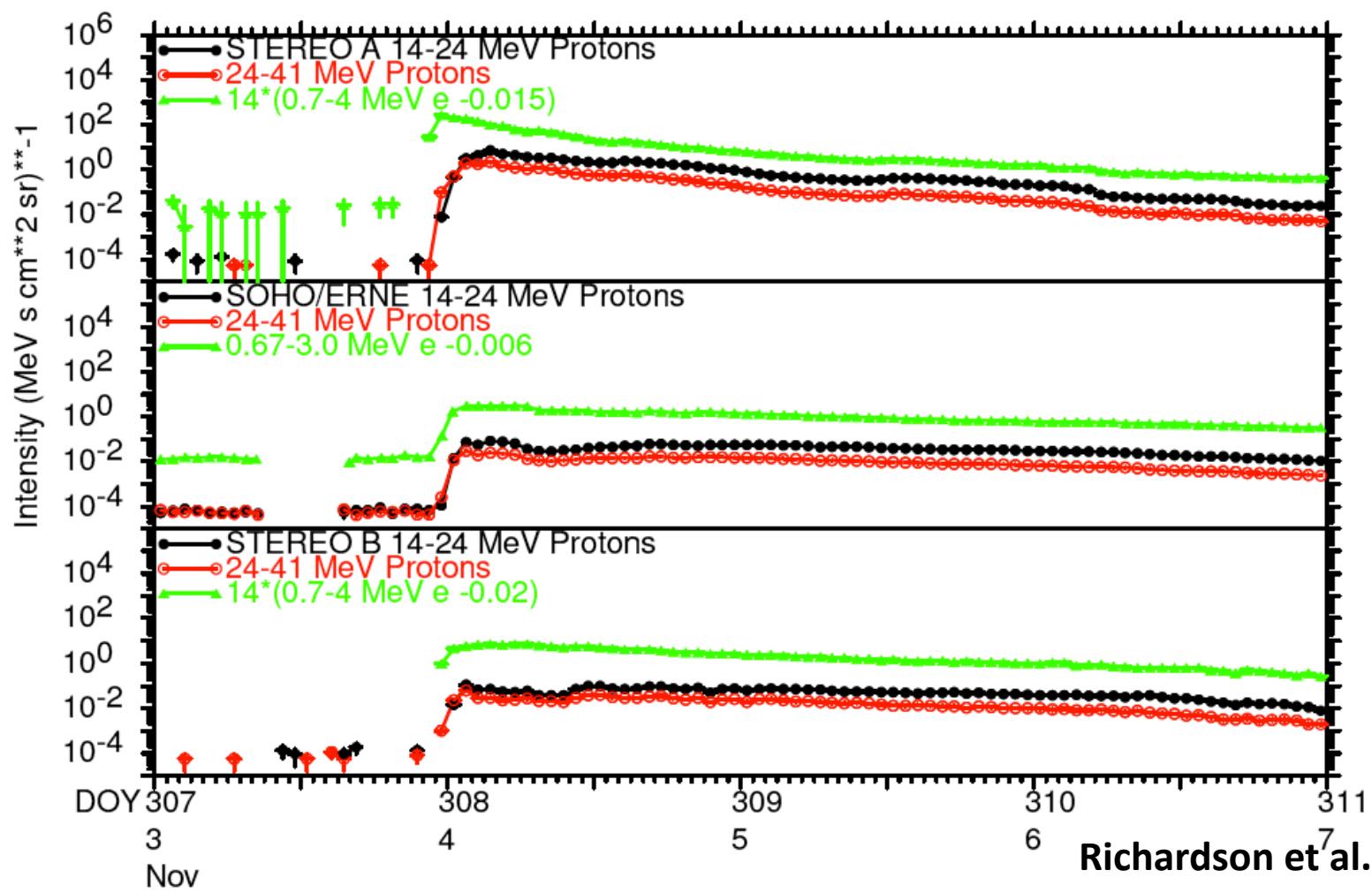
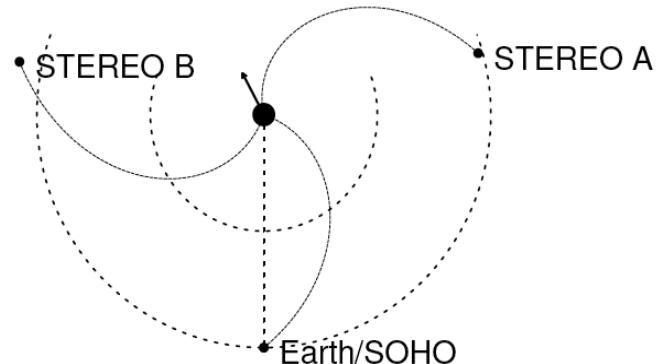


Daily Fluences of >10 MeV protons from NOAA's GOES satellites were integrated, starting with the beginning of cycles 22 (Sept 1986), 23 (June 1996) and 24 (December 2008).

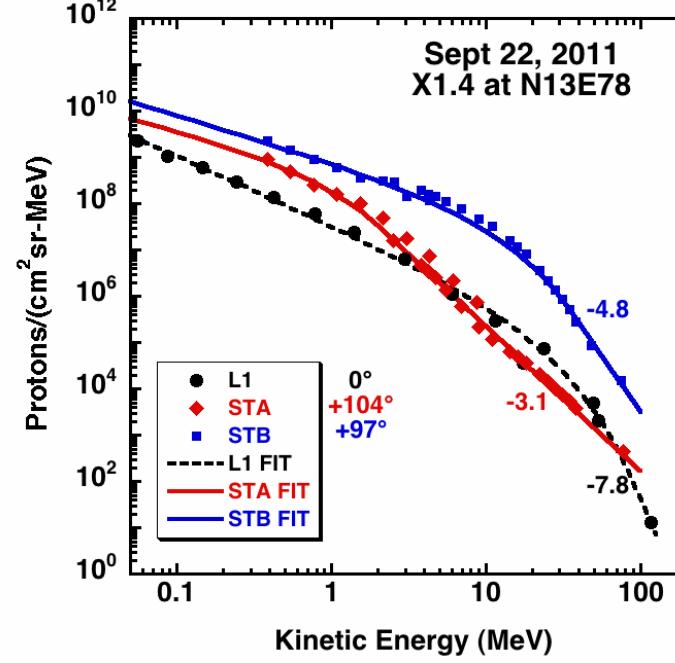
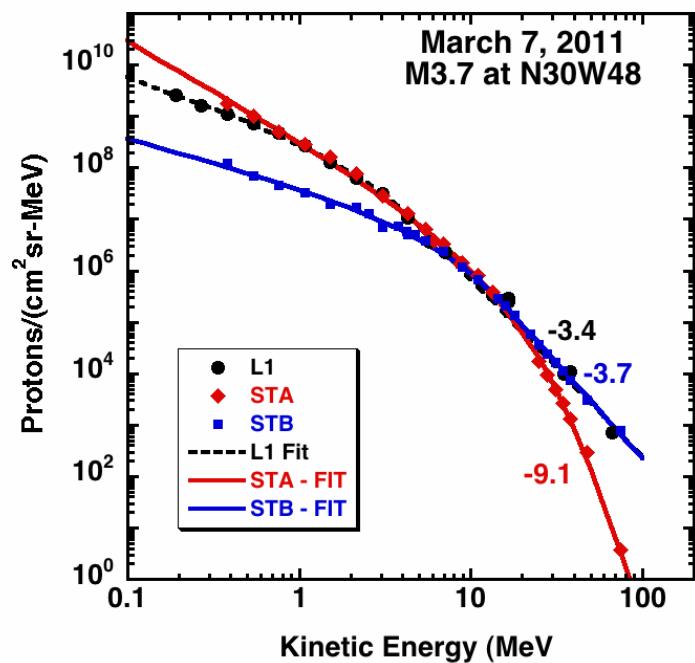
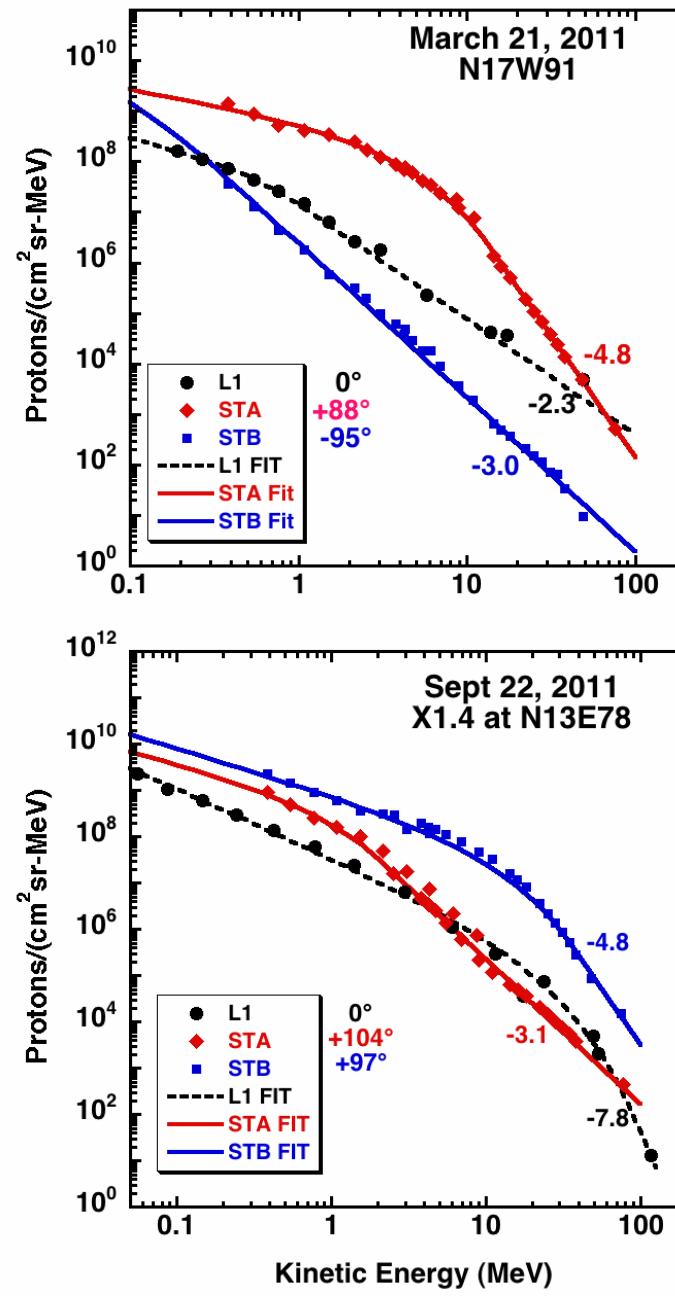
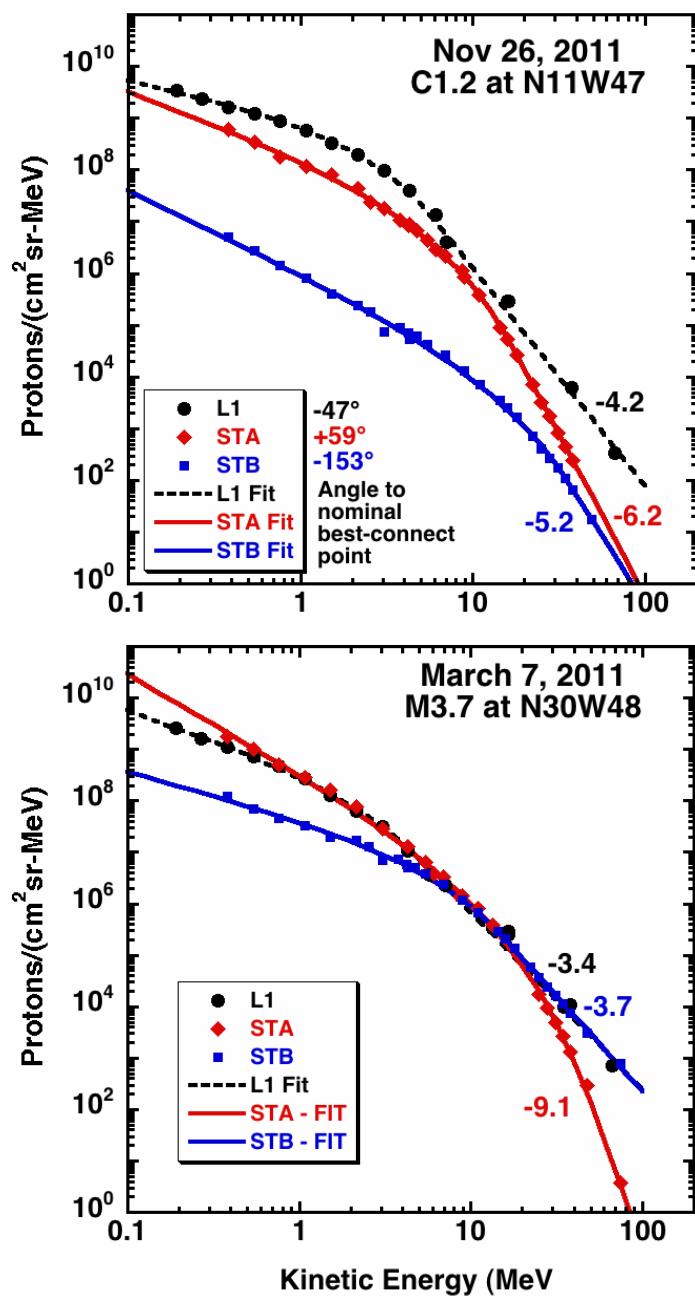
The two STEREOs measured similar fluences to those at Earth



How are particles transported so quickly
In longitude? In the Nov. 3, 2011 event
protons reached STEREO-B & Earth 24 min.
after reaching STEREO-A, the best connected
spacecraft

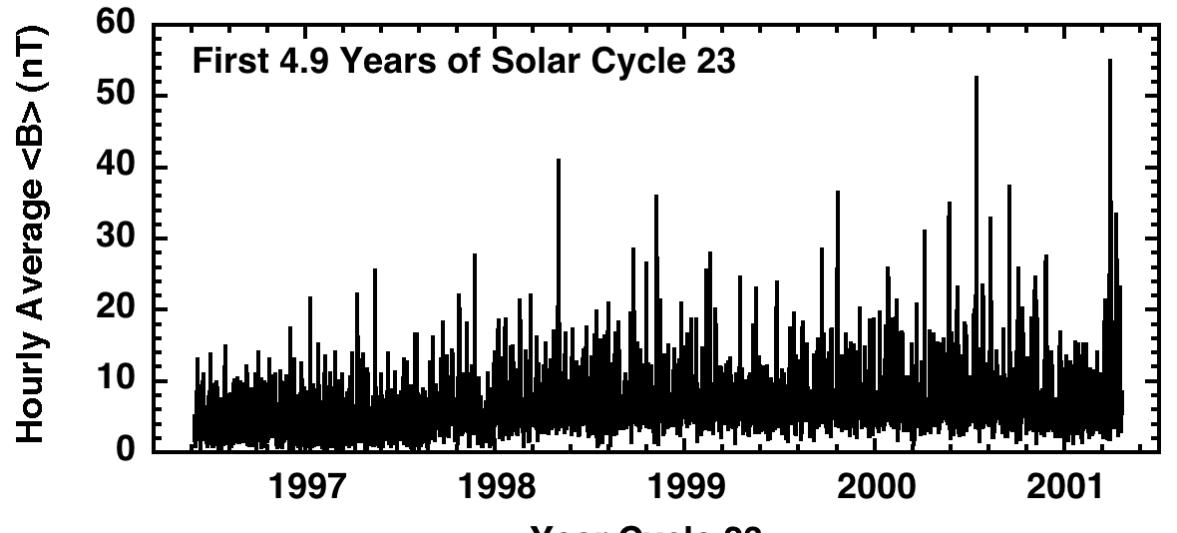


There is a surprising degree of variation in fluence spectra from the same event

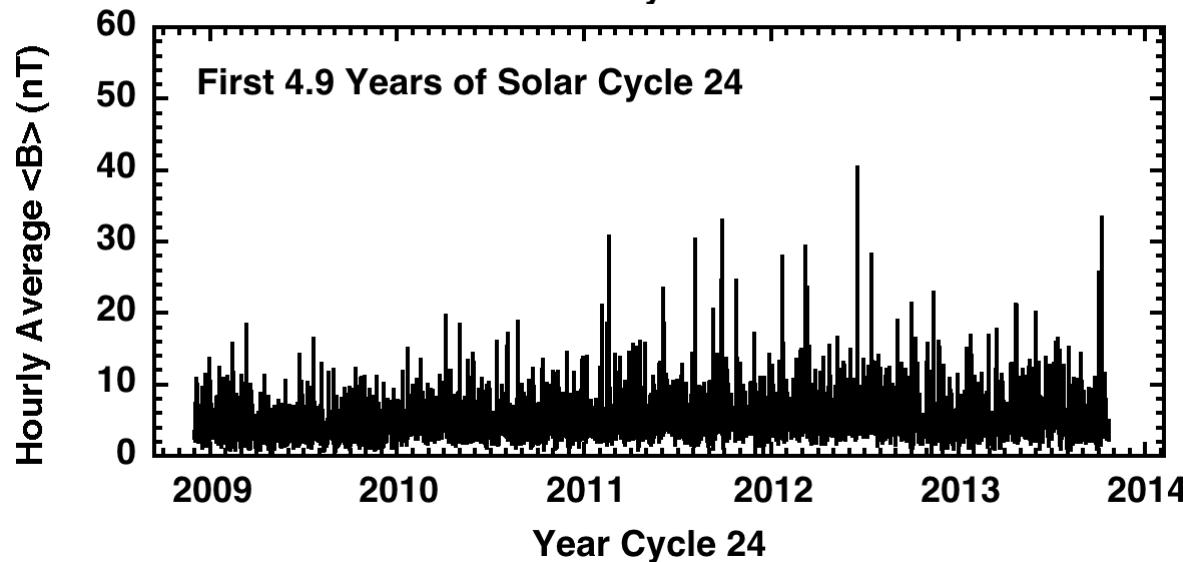


Why so few large SEP events?

The interplanetary magnetic field is significantly weaker during cycle 24
(as it was during the extended solar minimum).
This lowers the efficiency of SEP shock acceleration

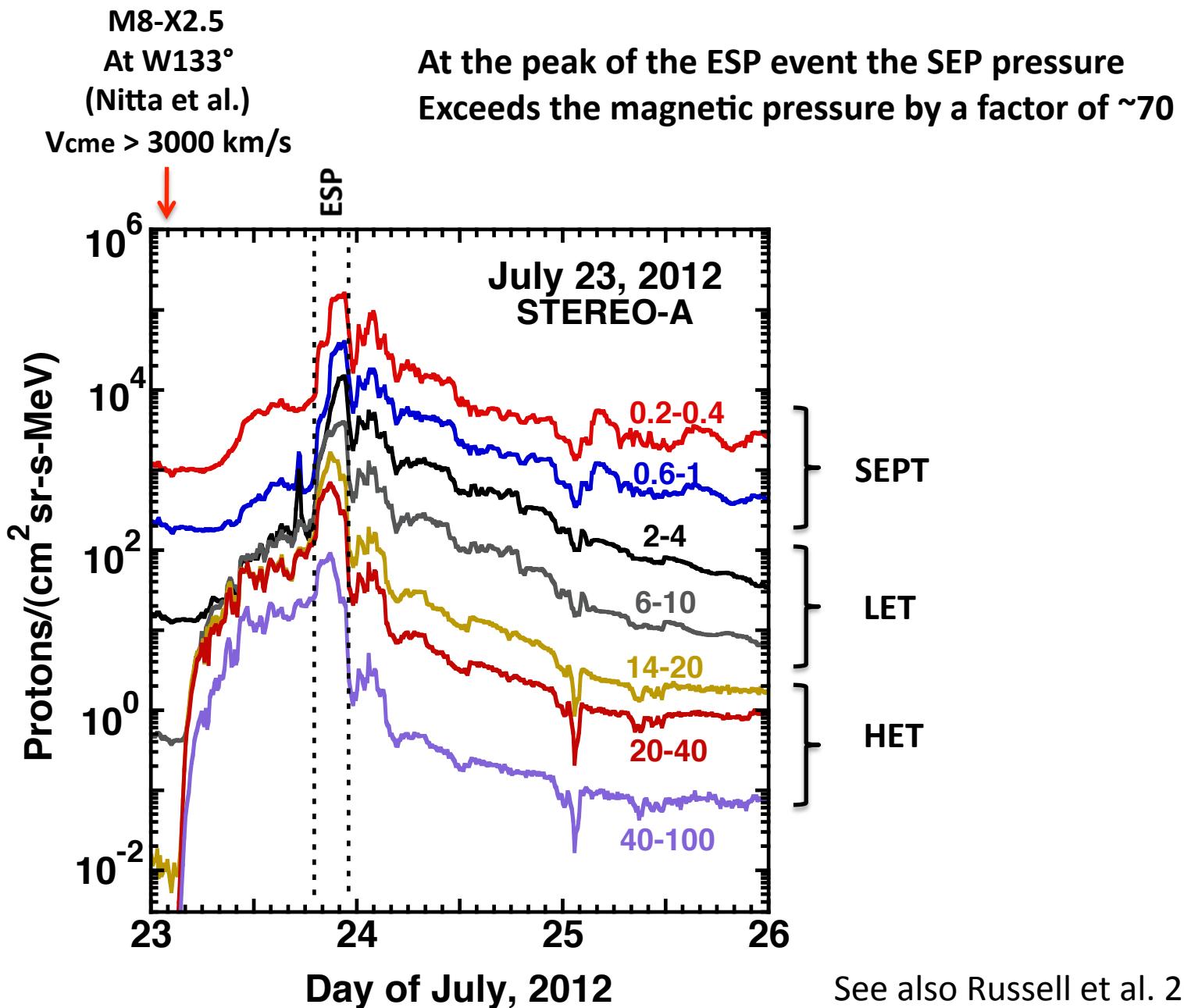


$$\langle B \rangle = 6.48 \text{ nT}$$



$$\langle B \rangle = 4.97 \text{ nT}$$

Time history of the July 23, 2012 SEP Event at STEREO-A



NOAA Top 20 Solar Proton Events
GOES >10 MeV Protons: 1976 – 2013
(Total of 249 Events)

| Rank | Year | Month | Start | Intensity P/(cm ² sr-s) |
|------|------|-------|---------|---------------------------------------|
| 1 | 1991 | Mar | 23/0820 | 43000 |
| 2 | 1989 | Oct | 19/1305 | 40000 |
| 3 | 2001 | Nov | 04/1705 | 31700 |
| 4 | 2003 | Oct | 28/1215 | 29500 |
| 5 | 2000 | Jul | 14/1045 | 24000 |
| 6 | 2001 | Nov | 22/2320 | 18900 |
| 7 | 2000 | Nov | Aug-50 | 14800 |
| 8 | 2001 | Sep | 24/1215 | 12900 |
| 9 | 1994 | Feb | 20/0300 | 10000 |
| 10 | 1989 | Aug | 12/1600 | 9200 |
| 11 | 1989 | Nov | 30/1345 | 7300 |
| 12 | 2012 | Mar | 07/0510 | 6530 |
| 13 | 2012 | Jan | 23/0530 | 6310 |
| 14 | 2005 | Jan | 16/0210 | 5040 |
| 15 | 1992 | May | 09/1005 | 4600 |
| 16 | 1989 | Sep | 29/1205 | 4500 |
| 17 | 1989 | Mar | 08/1735 | 3500 |
| 18 | 2005 | May | 14/0525 | 3140 |
| 19 | 1991 | Jun | 04/0820 | 3000 |
| 20 | 1982 | Jul | 11/0700 | 2900 |

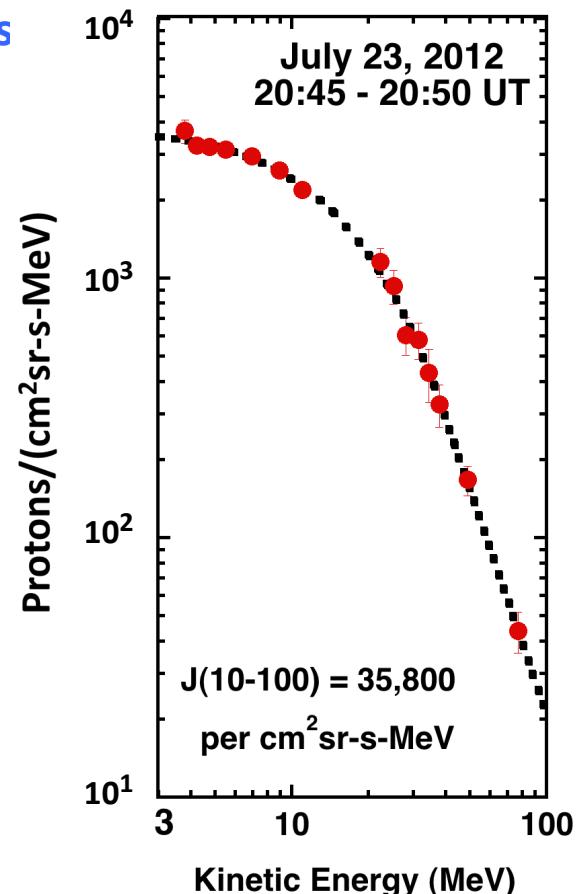


Cycle 23 events

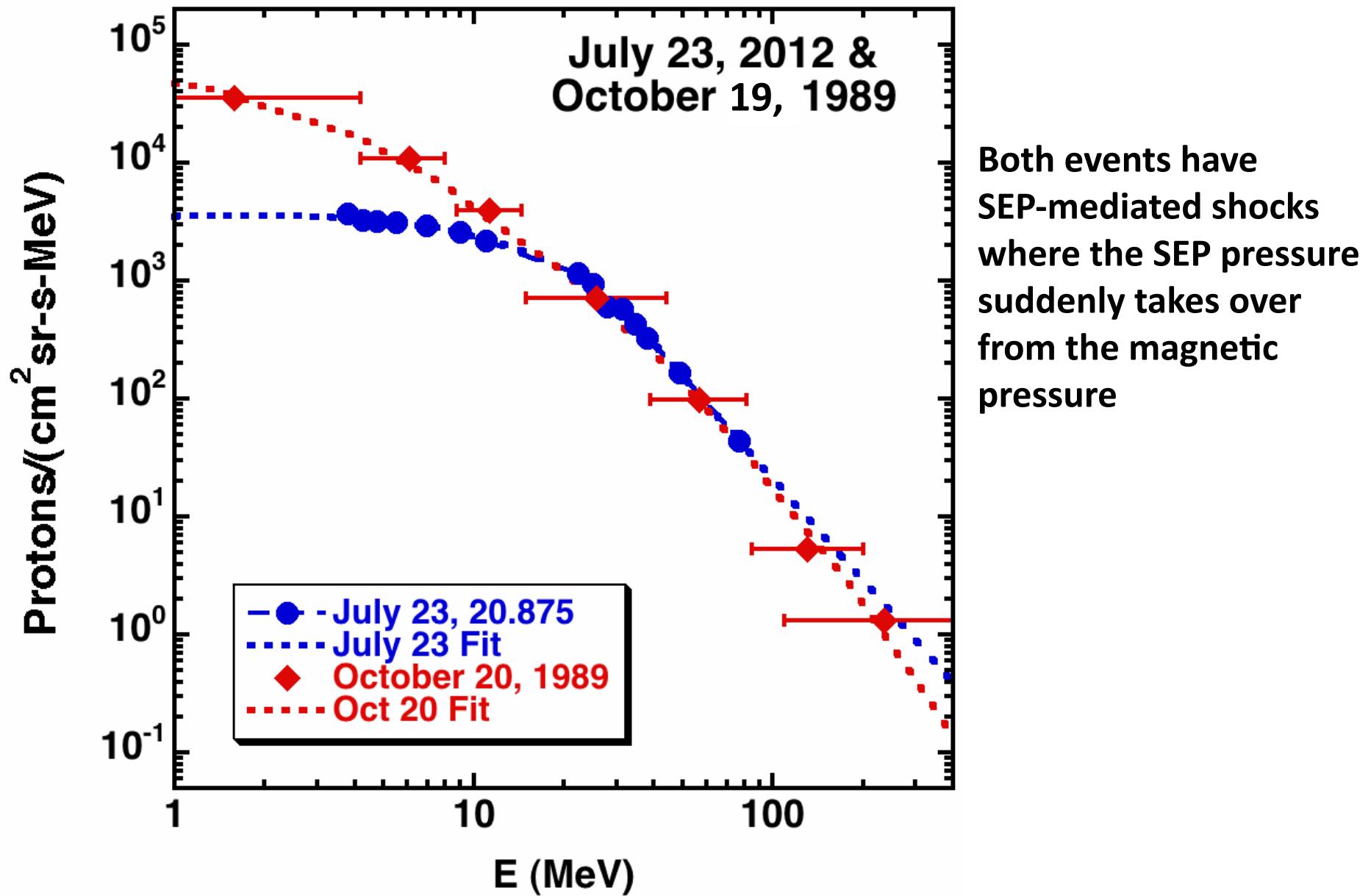


Cycle 24 events

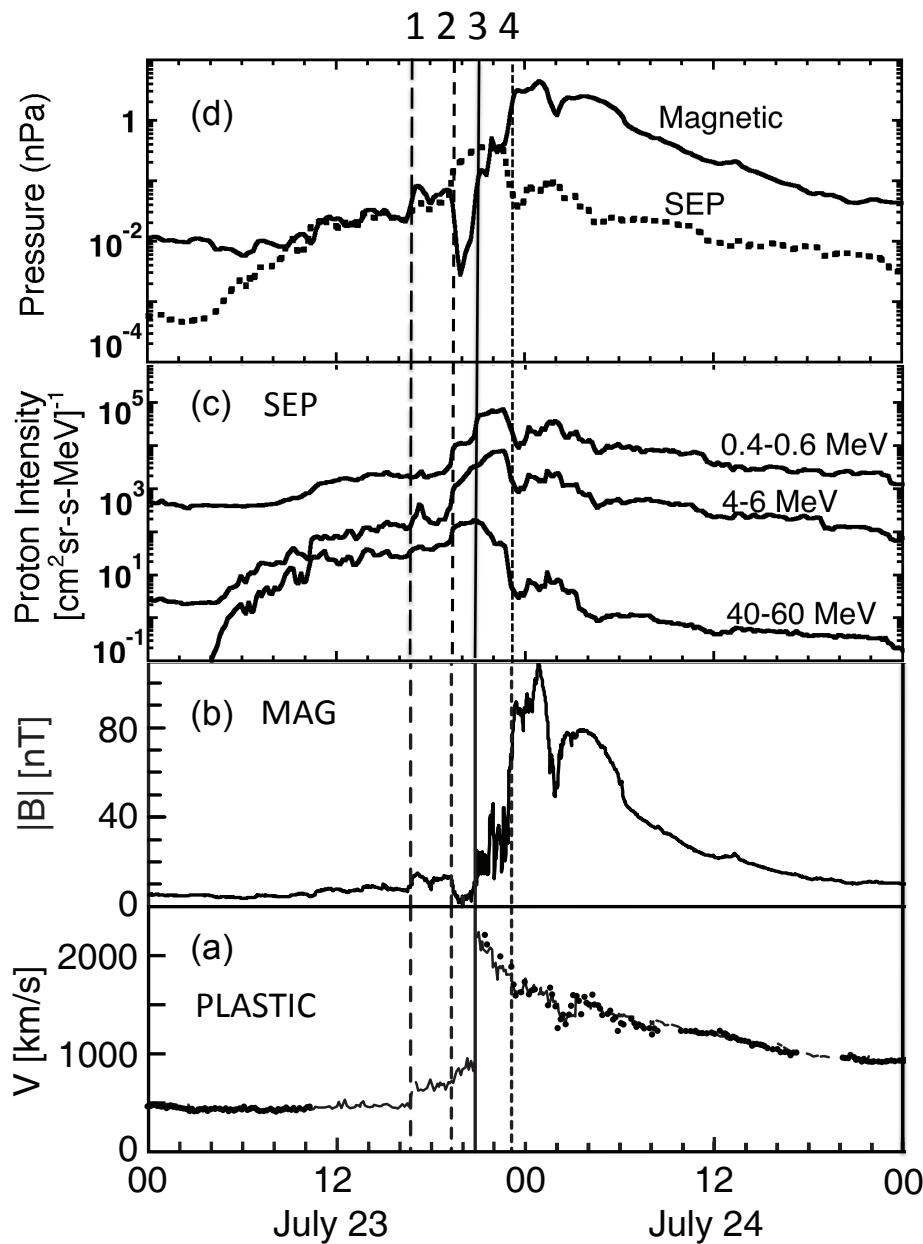
July 23, 2012
 $= 35800$
 p/cm^2s



The July 23, 2012 event is very similar to the October 19, 1989 Event studied by Lario & Decker (2002).



Overview of the July 23, 2013 Event



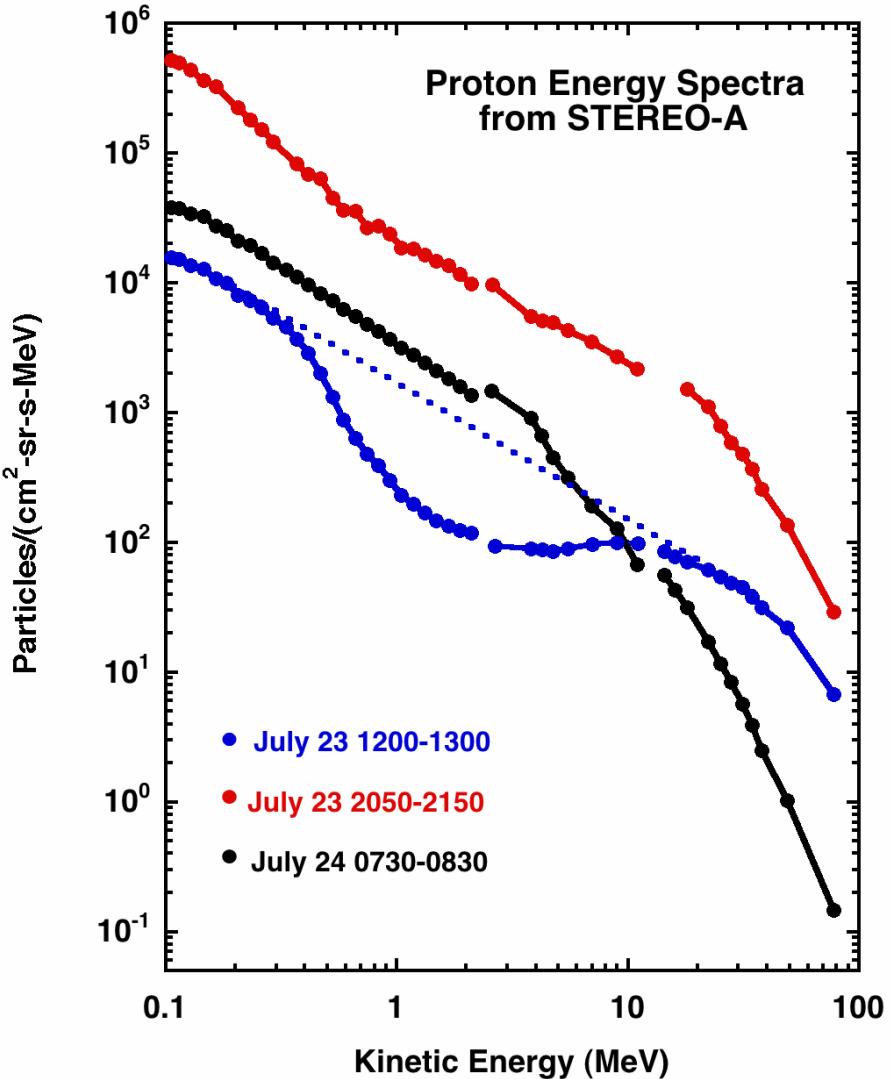
- 4) The leading edge of the magnetic cloud arrives at 2255 UT. B jumps to >80 nT and the SEP intensity suddenly drops. B eventually reaches 109 nT!
- 3) At ~ 2050 the SW speed jumps abruptly to a record-setting ~ 2250 km/s and B increases from ~ 5 to ~ 20 nT (a,b). This appears to be a fast mode shock
- 2) At 1915 UT the magnetic field (B) drops suddenly, the SEP intensity increases at all energies, but V_{sw} does not change. Note in (d) that the SEP pressure suddenly increases to replace the missing magnetic pressure. This is expected at a slow-mode wave. **SEP pressure = 70X magnetic pressure!**
Example of an SEP-mediated shock!
- 1) Initial disturbance arrives at 1630 UT (a,b). The mean transit velocity was ~ 2780 km/s.

Russell et al 2013; Mewaldt et al. 2013

Summary

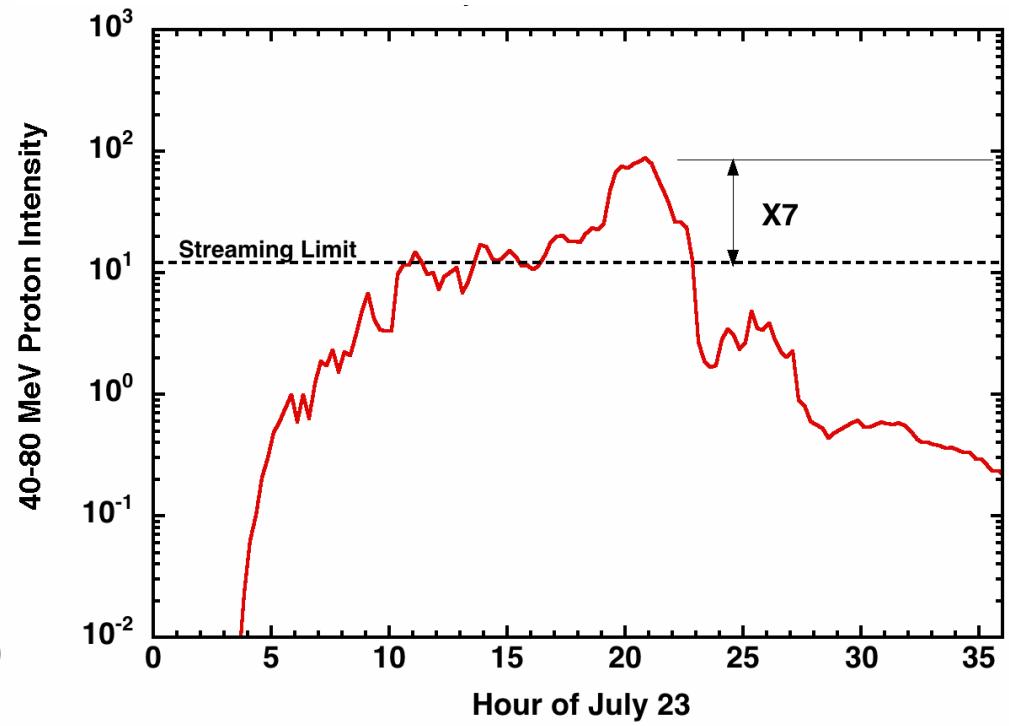
- The number of “GOES-Class” events at all three locations (28,28,27) is similar, but lower than those in cycle 23 (36), or than the average of cycles 21-23 (40).
- The 5-year cycle-24 >10 MeV fluences are significantly lower than in cycles 22 and 23 due mostly to the smaller number of very large SEP events [>1000 protons/(cm²s-s)].
- Many large SEP events are “GOES events” over a wide range of longitudes – how are they transported so easily and quickly?
- The July 23, 2012 SEP event observed at STEREO-A is comparable in intensity and fluence to the largest events of the space age in several respects.
- Overall, the most significant difference between cycles 23 and 24 is the lower interplanetary magnetic field strength, which affects both the acceleration and transport of energetic particles near the Sun.

Extras



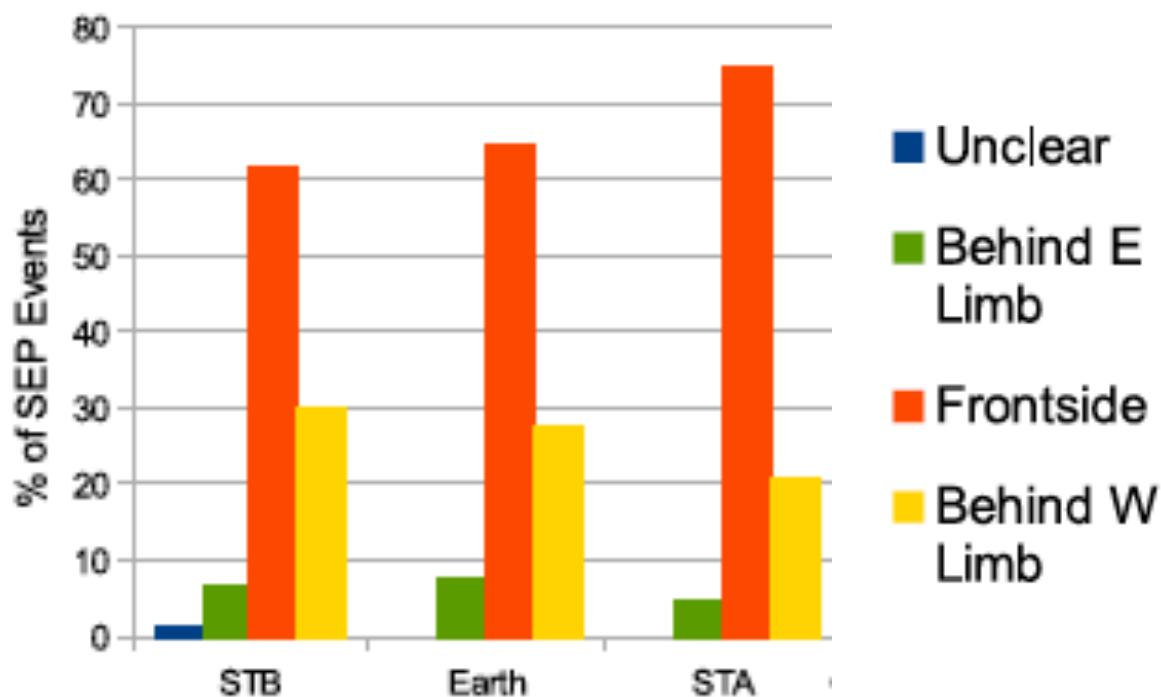
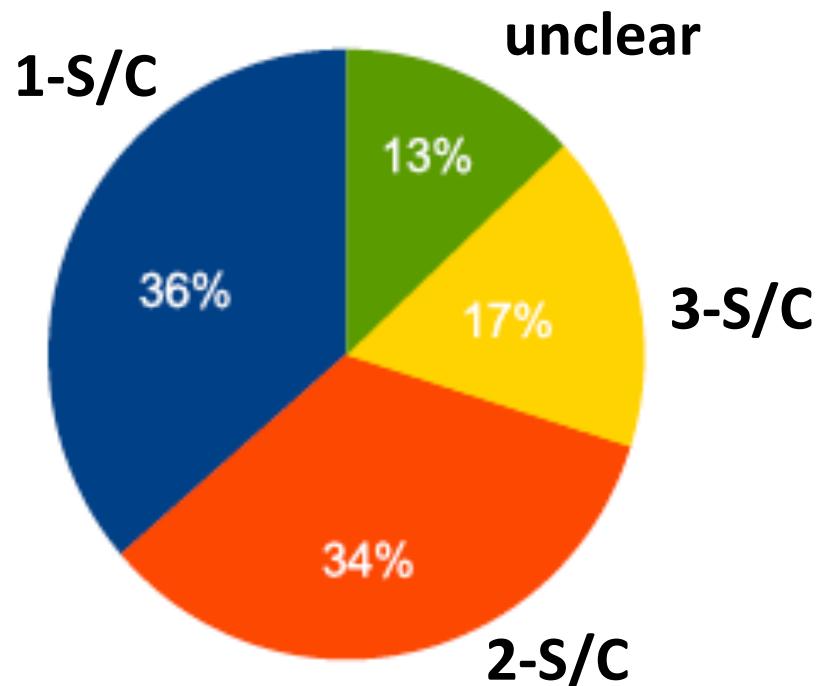
Adapted from Russell et al. 2013, Figure 4

Effects of the Streaming Limit



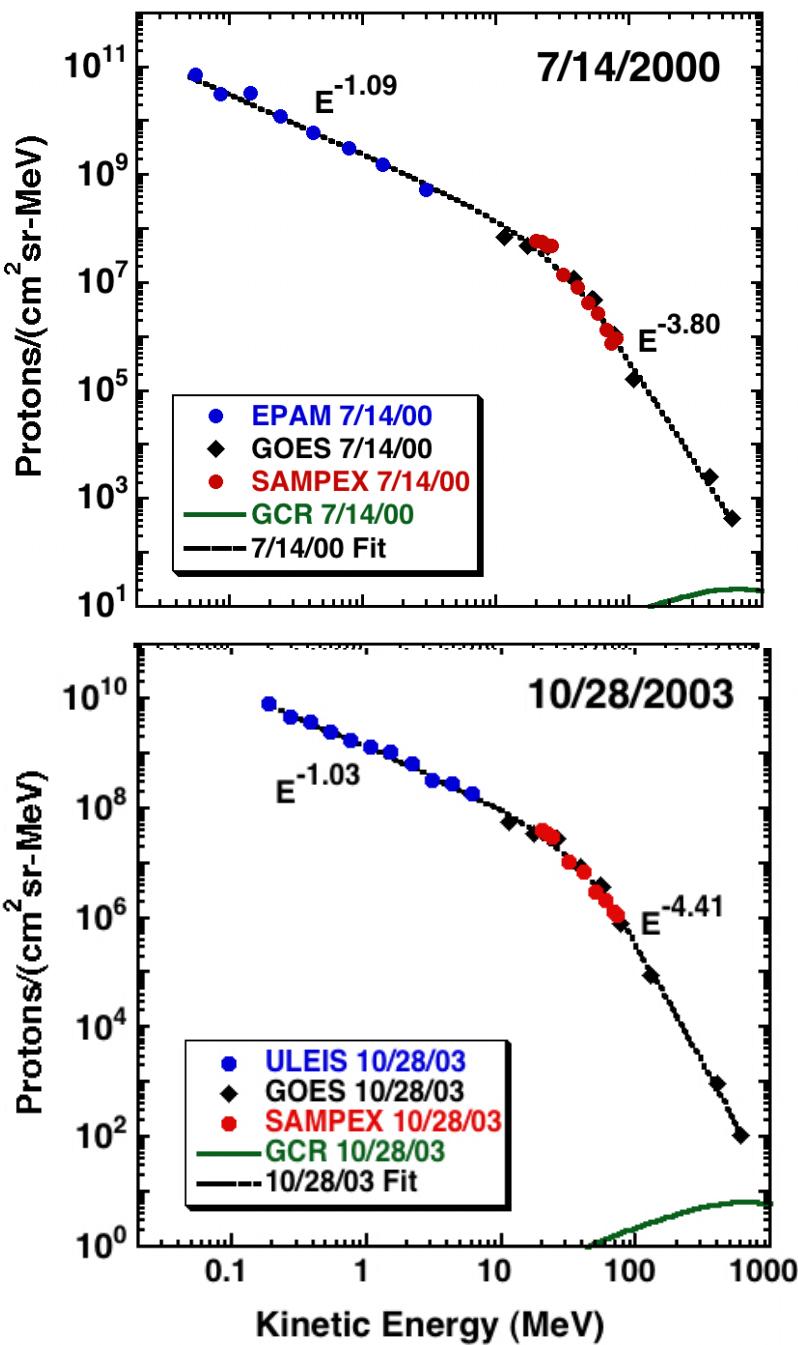
See Reames and Ng

About 50% of 25 MeV proton events are observed at more than one spacecraft

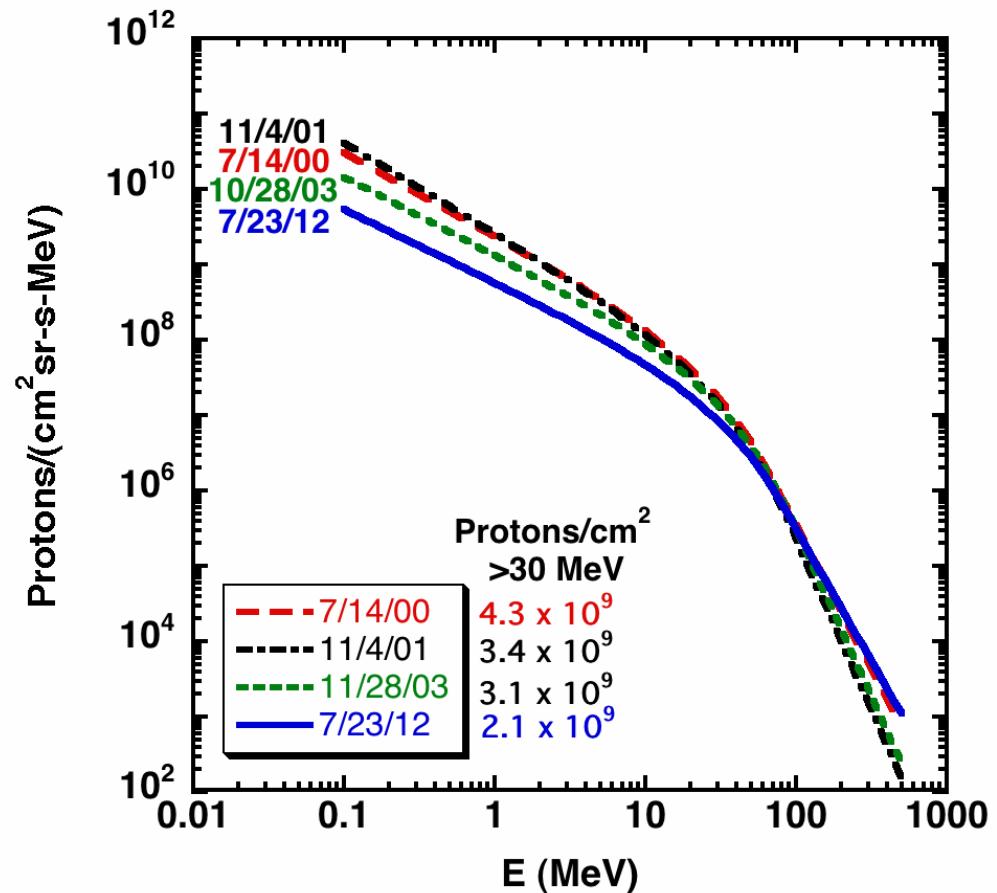


About 30%-35% of 25 MeV proton events originate beyond the west or east limbs

Richardson et al. 2014



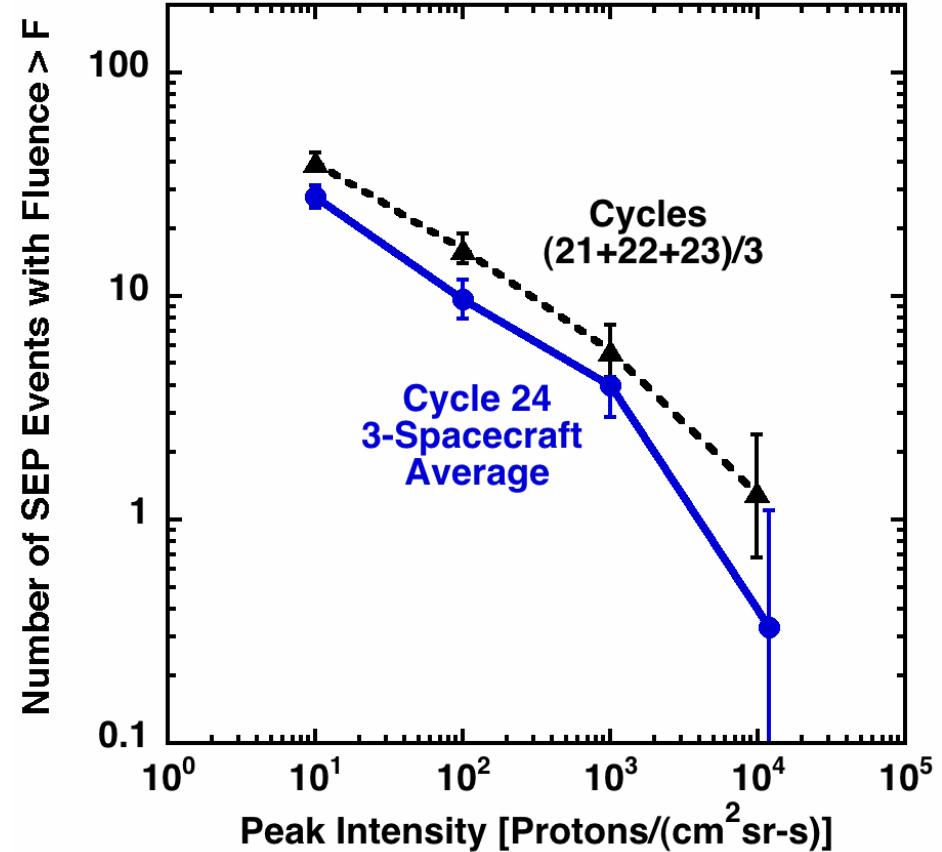
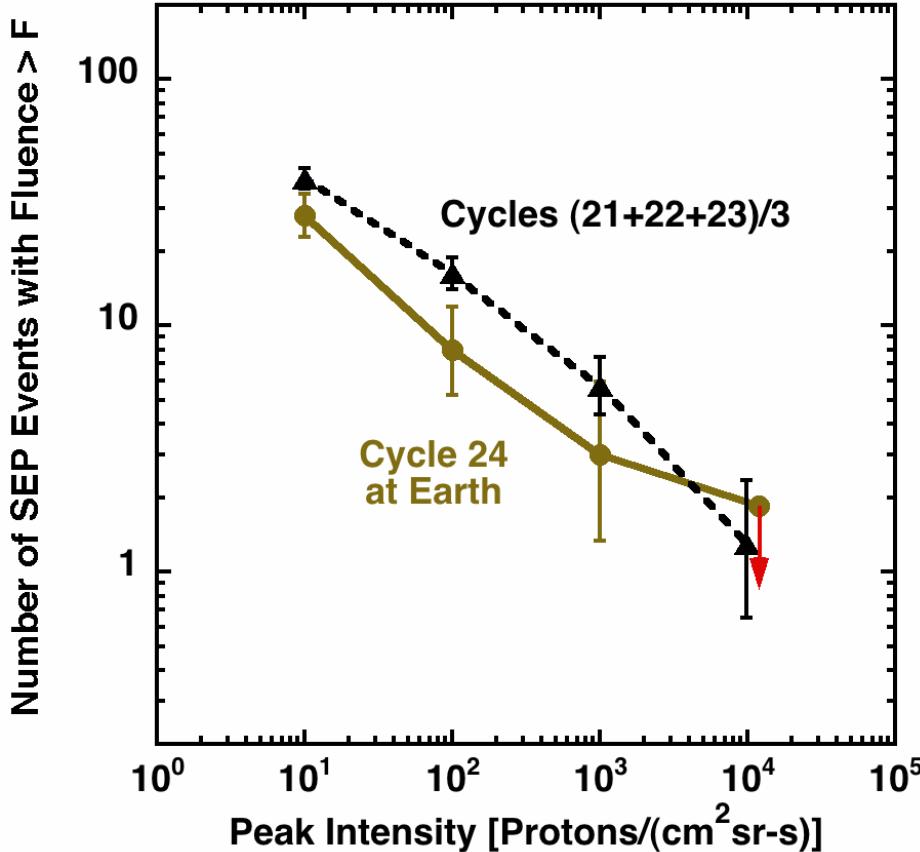
The July 23, 2012 proton fluence was comparable to that of the largest events of cycle 23. It most likely would have been a ground-level event and produced a record-breaking geomagnetic storm



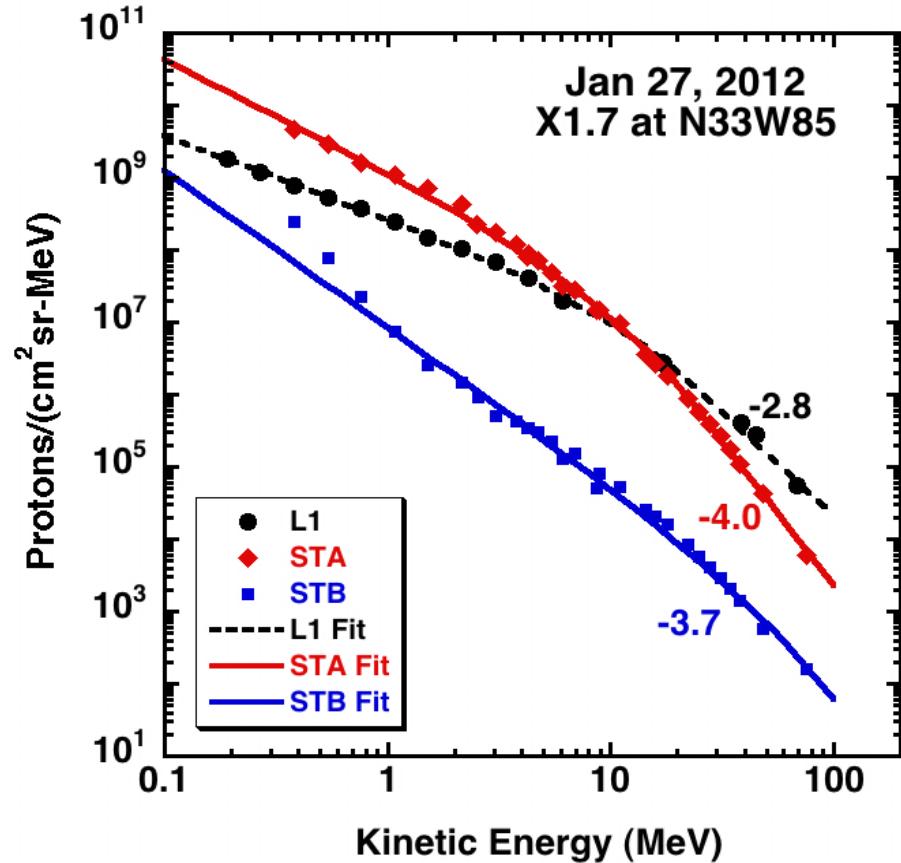
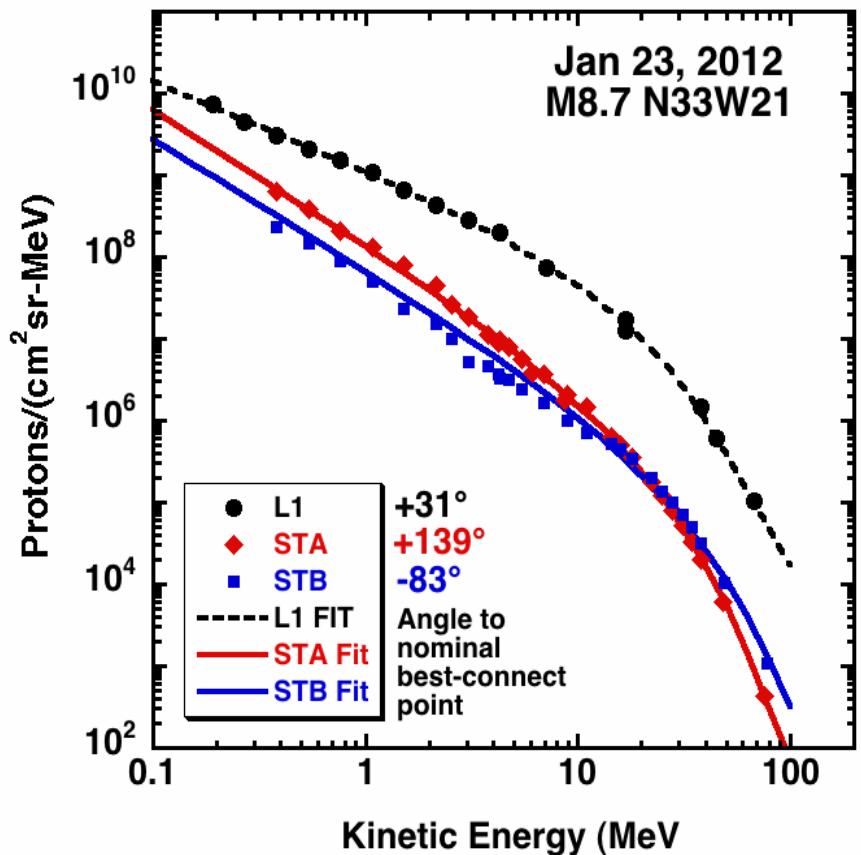
SEP Peak Intensity Distributions

Compare Cycle 24 with cycles 21-23 over first 5 years

Cycle 24 has had fewer events of all sizes than Cycles 21-23, but especially for events with $>10,000$ Protons/ $(\text{cm}^2 \text{sr-s})$, where cycles 21-23 had 4 events and cycle 24 has had only one event at three spacecraft (July 23, 2012 at STEREO-A).



These January 2012 Events were both observed at Mars



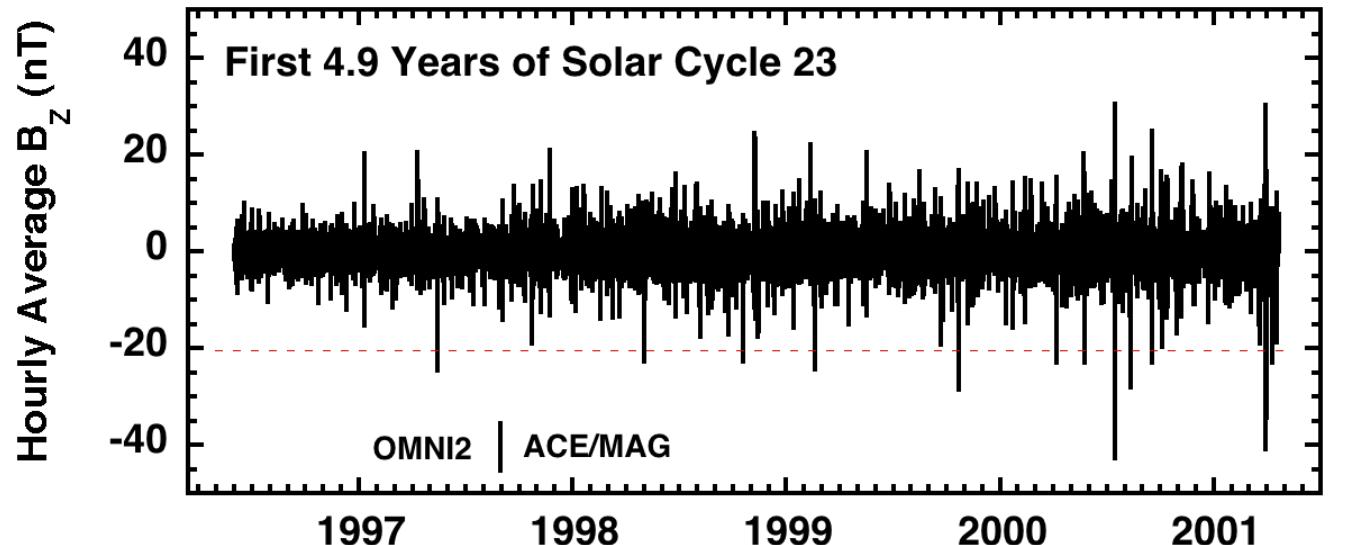
These fluence spectra were measured by instruments on several 1-AU spacecraft:

Near Earth: GOES/EPS; ACE/ULEIS or ACE EPAM; ACE/SIS; SOHO/EPHIN

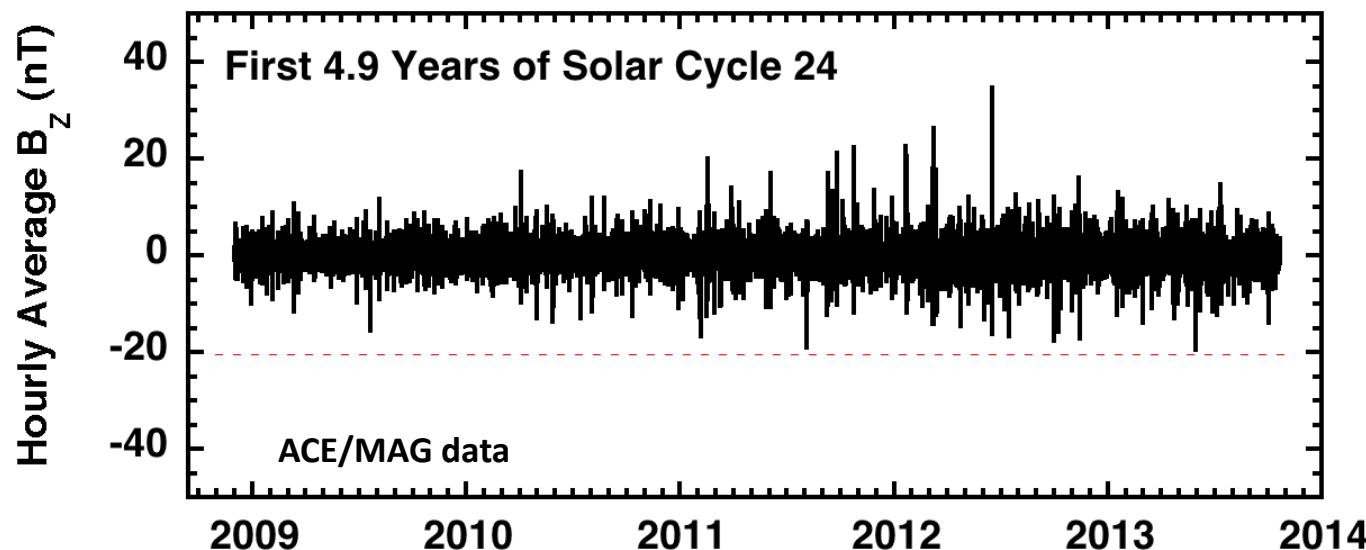
STEREO-A & B: HET, LET, & SIT (Still need to add SEPT to get to lower energy)

The fits were made with the broken-power-law function of Band et al. (1993).

It is negative B_z that is mainly responsible for geomagnetic storms driven by ICMEs.



**Very large fluctuations;
Many dips < -20 nT**



**Small fluctuations;
0 dips below -20 nT**